lower compression ratio than their diesel counterparts: 10.5 to 1 for the CNG engines versus 16.3 to 1 for the diesel engines, which also tends to lower efficiency.

An added disadvantage for the CNG buses is their weight—they weigh about 3,900 pounds more than their diesel counterparts. This weight penalty results largely from the weight of the CNG tanks, and increases the curb weight of a bus by about a 14% (the diesel control buses have a curb weight of approximately 27,000 pounds). These three factors led us to expect that energy efficiency might be significantly reduced. A difference in the fuel economy of the CNG and diesel buses was observed both in the average results and the dynamometer results. The fuel economy of the CNG buses was about 10 to 20% lower than that of their diesel counterparts.

Alcohols

The alcohol buses also suffer from weight penalties. The alcohol option results in a weight penalty of between 1,000 and 1,500 pounds, depending on the fuel tank capacity. In addition, the alcohol buses at the Miami site have an additional weight penalty of 1,200 pounds, which is partially due to options and specifications unrelated to the alcohol fuel engine. We expected this extra weight to reduce the fuel economy of the alcohol buses.

In addition, the alcohol buses have very high compression ratios (more than 20 to 1), which was expected to lower fuel economy because of higher friction losses (such as piston side loading). The results to date, however, indicate that the alcohol fuel buses at all the sites are performing very well, delivering fuel economy comparable to that of the diesel control buses on an equivalent energy basis. (Note that the diesel control buses at Peoria are equipped with particulate traps, which are known to lower fuel economy slightly.)

Biodiesel

The St. Louis biodiesel buses exhibited approximately 6% lower average fuel economy than the diesel control buses. Dynamometer data also showed a similar drop in fuel economy. Because the fuel economies quoted are already based on diesel equivalent gallons to eliminate any differences in fuel energy content, we did not expect this drop. We are currently investigating the cause of this drop.

In summary, the fuel economy results are in line with expectations from the various engine technologies, with the possible exceptions of the LNG dual-fuel engine, and the biodiesel buses, where the reason for the lowered fuel economy is not readily apparent.

Costs

The cost of operating alternative fuel buses versus their diesel controls can be broken down into operating and capital costs. These categories can, in turn, be broken down further. Operating costs consist of fuel, oil, maintenance, and repair costs. Capital costs consist of the additional costs of the alternative fuel bus and the costs of modifying the facilities for alternative fuel use.

Operating Costs

Fuel Costs

In September 1994, the price paid for a gallon of diesel fuel by the transit agencies varied from about $0.47 to $0.67. The price paid per diesel equivalent gallon varied considerably for some of the alternative fuels. The price paid for CNG was the lowest, at $0.55 to $0.69 per diesel equivalent gallon (this price excludes the cost of the electricity needed to compress the fuel — we are currently calculating this cost and will present it in future reports). Methanol prices have been volatile in recent years. At $2.29 per diesel equivalent gallon, M100 was the most costly of the alternative fuels in the test program. The price paid for E95 was about $1.80 per diesel equivalent gallon. Early in 1994 the Peoria Transit Agency switched from using E95 to E93 to take advantage of a $0.43 per gallon "blenders credit," which lowered their fuel cost to $1.21 per diesel equivalent gallon. The BD20 used in Missouri cost $1.00 per diesel equivalent gallon. In Houston, the cost of LNG has been $0.80 per diesel equivalent gallon.

In general, alternative fuel prices have varied more than those of diesel fuel, both regionally and over time. For example, CNG prices differ significantly from region to region, and methanol prices nationwide have been volatile recently. As their use increases, the price volatility of alternative fuels should moderate.

Table 2. Maintenance Costs for the Buses

		Houston LNG	Miami CNG	Tacoma CNG	Peoria E95/E93	Minn E95	Miami M100	St. Louis BD20
Number of Buses	AF DC	10 5	5 5	5 5	5 3	5 5	5 5	5 5
Mileage in Program	AF DC	375,694 431,797	87,329 311,813	293,753 537,884	388,654 225,377	57,245 170,731	193,357 368,408	165,017 204,036
Engine/fuel system related maintenance costs* per 1,000 miles	AF DC	$92 $38	$101 $63	$51 $54	$45 $25	$94 $31	$115 $77	$57 $41
Total bus maint. costs per 1,000 miles	AF DC	$247 $198	$243 $312	$124 $136	$150 $120	$207 $176	$229 $256	N/A N/A

* Includes maintenance in the engine, fuel system, exhaust, cooling, air intake, ignition, cranking, charging, and general electrical areas. Excludes all other areas of the bus.

AF = Alternative Fuel DC = Diesel Control N/A = Not Available

Maintenance Costs

We are tracking maintenance costs on all the buses. We receive copies of all the work orders and parts replaced on the entire bus from the transit agency. The work performed and parts replaced are coded by type of work (scheduled maintenance, unscheduled maintenance, road calls, and configuration changes to the buses), as well as by vehicle subsystem such as engine, fuel, exhaust, and suspension. Labor hours are also recorded and a standard labor rate of $15 per hour is used to calculate the labor costs for each of the transit agencies. Maintenance cost data in this report do not include warranty work performed on the buses because the agencies do not bear the cost of this work (except for the in-house labor cost for warranty repairs—these costs are generally paid by the transit agencies and are included in the maintenance costs presented in this report).

Table 2 shows the maintenance costs for the buses in the program. The maintenance costs have been totaled in two different ways. First, we calculated the engine/fuel system related costs. This includes the maintenance costs for the engine, fuel system, exhaust, cooling, air intake, ignition, cranking, charging and general electrical system, because these areas are most likely to be affected by the alternative fuel. We also calculated the total maintenance costs for the entire bus. An alternative fuel bus will sometimes have higher engine/fuel system related maintenance costs but these are often overshadowed by costs for repairs on other parts of the bus, such as the air conditioning and heating system.

A few words of caution are necessary in using the data. Some of the fleets have many miles on the buses; others do not. As more miles are logged by the test vehicles, a better average maintenance profile emerges from the data. Also, comparisons of maintenance data from different agencies should not be made because each agency has a different system for recording and submitting data. Alternative fuel buses should only be compared with their diesel control buses at the same site. The sections that follow summarize maintenance costs by fuel type.

Liquefied Natural Gas—Total bus maintenance costs for the Houston dual-fuel buses (which run on LNG and diesel) have been about 25% higher than for the control buses. Engine/fuel system related costs were about $92 per 1,000 miles for the dual-fuel buses and about $38 per 1,000 miles for the diesel control buses. The higher costs of the dual-fuel buses are largely attributable to a few problem areas in the engine and fuel system. Significant problems occurred with the dual-fuel engine gas injectors. It is believed that dirt in the fuel injectors, possibly combined with other problems, caused the injectors to stick open. The engine manufacturer worked on the problem under warranty, but internal labor costs at Houston Metro were still significant. In addition, fuel system leaks have also been a source of cost in the LNG buses.

Compressed Natural Gas—In Tacoma, the total bus maintenance costs for CNG buses were approximately 9% lower than the diesel controls. Costs in the engine/fuel system related areas were 6% lower.

In Miami, the total maintenance costs for buses running on CNG was about 22% lower than the maintenance cost for diesel buses. The Miami CNG buses, however, have accumulated only 87,000 miles, whereas the diesel buses are one model year older and have accumulated more than 300,000 miles. Also, when the Miami diesel buses started in the program, they had already accumulated a significant number of miles. The data, therefore, reflect maintenance done during different periods in the buses' lives. We have requested back data on the diesel buses in Miami, and when we receive this information, we will re-do the analysis with comparable mileage and periods in the buses' lives. Even though the total maintenance costs for the buses were lower for CNG than diesel, the engine/fuel system related costs were higher: about $101 per 1,000 miles versus $63 per 1,000 miles for the diesel buses.

Tacoma has accumulated many more miles on its CNG buses than Miami: 294,000 versus 87,000. Therefore, greater emphasis should be placed on the Tacoma data than the Miami data.

Ethanol—The ethanol buses in Peoria exhibited total bus maintenance costs about 25% higher than their diesel counterparts. Engine/fuel system related costs for the ethanol buses were about $45 per 1,000 miles versus $25 per 1,000 miles for the diesel buses. The additional cost of maintaining the fuel system was the highest contributor to the overall maintenance cost increase. The high fuel system maintenance cost resulted primarily from the cost of ethanol fuel filters. The primary and secondary fuel filters together cost nearly $105 for ethanol, compared to about $6 for diesel. This cost differential probably results from the need to use ethanol-compatible materials and the limited demand for ethanol filters. The frequent replacement of fuel filters on the ethanol buses is a potential indicator of fuel quality problems. This was in fact the case, and Peoria recently replaced its refueling hose (which was found to be incompatible with ethanol) to make the system fully ethanol compatible.

Electrical system maintenance costs were also higher for the ethanol buses because two starters, several batteries, and nine glow plugs had to be replaced.

Total maintenance costs on the Minneapolis/St. Paul ethanol buses were about 18% higher than those for the diesel control buses. Engine/fuel system related costs were significantly higher for the ethanol buses—about $94 per 1,000 miles versus $31 per 1,000 miles for the diesel controls. As in Peoria, the higher maintenance cost was primarily in the fuel system area and attributable largely to the cost of the ethanol fuel filters. Again, fuel filter fouling may result from poor fuel quality caused by ethanol-incompatible materials in the fuel delivery system.

Methanol—The Miami buses running on methanol have had lower total bus maintenance costs than their diesel control buses (about 10% lower), but the costs related to the engine fuel system have been about 50% higher. Many of the buses' fuel filters had to be replaced, and methanol fuel filters cost Miami about $72 per set versus $6 per set for diesel. As with the Miami CNG buses, that the diesel control buses are older and have accumulated more mileage on them than the M100 buses. We have requested back data on these buses from the Miami transit agency. Adding New York as a second methanol site will aid in the cost analysis of methanol buses.

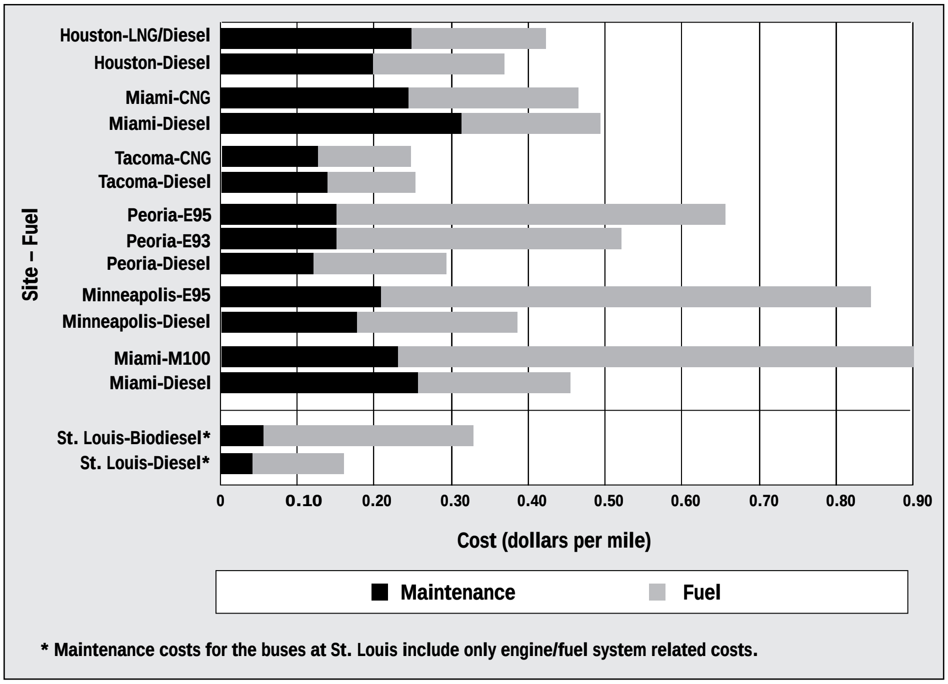

Figure 6. Average maintenance and fuel cost per mile traveled

Biodiesel—In St. Louis, we collected only maintenance data for the engine-and fuel-related systems, because the test fleet consisted of older buses that had been retrofit with re-built engines for the program. The engine/fuel system related maintenance costs for the biodiesel buses operating in St. Louis were about $16 per 1,000 miles higher than those for their diesel counterparts. Much of this cost difference arises from having to replace several injectors on the biodiesel buses just as this report was going to press. We are investigating the cause of the replacements. Only 165,000 miles have accumulated on these buses so far. We plan to add a second biodiesel site in the near future.

Cost per Mile Traveled

Figure 6 shows the average fuel and maintenance costs per mile traveled. In all cases, the oil cost was insignificant compared to the fuel and maintenance costs. We calculated the fuel cost per mile using the representative average in-use fuel economy and the actual fuel cost paid by the transit agencies. Neglecting the cost of compressing the natural gas, the fuel and maintenance cost per mile for test buses running on CNG has been about the same as those for buses running on diesel fuel. However, the fuel and maintenance costs for all of the buses using alcohol fuel and buses using BD20 have been about twice as high as the costs for buses using diesel. The costs for LNG/diesel buses have been about 14% higher than for their diesel counterparts.

Capital Costs

Adding alternative fuel buses to a fleet requires not only that the buses be acquired, but also that changes be made to the refueling, maintenance and storage facilities at the site (in most cases). The capital costs presented in this section are based on data collected from the transit agencies as well as studies of representative costs nationwide.

Additional Bus Acquisition Costs

At this time, buses running on alternative fuels are more expensive than those running on diesel. Higher engine costs represent a significant portion of this increased expense. Because these engines are early production engines, the manufacturers have been charging about $15,000 to $30,000 more for an alternative fuel engine than for a diesel engine. We expect that, as their production volume increases, the cost of alternative fuel engines will begin to approach that of their diesel counterparts.

There is, however, insufficient information to indicate if they will equal the cost of diesel engines some time in the future.

Biodiesel buses are the exception to the rule. Because the buses running on BD20 in this program use conventional diesel engines, there is no additional acquisition cost. (It should be noted, however, that currently biodiesel is not approved by most engine manufacturers as a diesel substitute. Because the use of biodiesel may affect engine warranty claims, a transit agency should check with the engine manufacturer before using the fuel).

The fuel tanks of alternative fuel buses are also generally more expensive than diesel fuel tanks. These additional costs can run from $5,000 for a bus operating on E95 to around $20,000 for one operating on CNG. Again, fuel tanks represent no additional expense for buses running on biodiesel.

Table 3 presents estimated incremental costs (over and above a diesel-fueled bus) for new alternative fuel 40-foot transit buses. The incremental costs for a propane-fueled bus have been included because we will add a propane site to the program in the near future. These prices are only for comparison purposes; actual bus prices will vary with each transit property because of variations in vehicle specifications and the size of the order.

Table 3. Incremental Capital Costs of 40-Foot Buses by Fuel Type (1994 $).

(The base price for a diesel bus is $215,000.)

Fuel Type	Incremental Cost
Diesel	Base
LNG	$55,000
CNG	$50,000
Ethanol	$20,000
Methanol	$20,000
Biodiesel	$0
Propane	$40,000

Source: Battelle

The current cost estimates reflect market prices after a few years of alternative fuel bus production experience. The technology is not yet mature. Before products reach the mature stage, prices are usually higher because of production start-up problems and unknown warranty exposure. Manufacturers charge a premium for early production models of alternative fuel bus engines, but that premium should decrease over time. We obtained these cost estimates from transit agency bus bids and in conversations with bus manufacturers.

Facilities Costs

Transit buses are stored and refueled centrally in facilities owned and operated by transit agencies. As a result, the capital and operating costs for any changes made to a facility to accommodate alternative fuel buses are important to consider when calculating the overall cost of operating with alternative fuels. The capital and operating costs for new facilities or modifications to existing facilities vary considerably, even for one type

Table 4. Maintenance and Storage Facility Modifications for Alternative Fuel Transit Bus Fleets

Fuel	Ventilation	Electrical	Heating	Other	Comments
Natural Gas (CNG and LNG)	At ceiling highest points	No overhead sparking contacts	No open flame heaters overhead	—	Requires sensors for combustible fuel detection
Ethanol	No change*	Unclassified electrical 18 inches above finished floor, no change*	No change*	Requires cistern for drain to trap fuel leakage	No ignition sources in floor area (18 inches and lower)
Methanol	No change*	Unclassified electrical 18 inches above finished floor, no change*	No change*	Requires cistern for drain to trap fuel leakage	No ignition sources in floor area (18 inches and lower)
Biodiesel Blend	No change	No change	No change	—	—
Propane (LPG)	Forced ventilation within 18 inches of floor	Unclassified electrical 18 inches above finished floor, no change*	No change*	—	No ignition sources in floor area (18 inches and lower). See also Note 1 below.

*If facility is certified for gasoline fuel.

Note 1: Additional considerations for propane facilities: Propane fuel tanks should never be overfilled, because thermal expansion of the fuel can actuate the tank relief valve. However, both facility codes and design practices often make some allowance for this contingency. Thus, the installation of propane gas detection systems in areas where propane-fueled vehicles are parked or maintained may be required by local authorities or considered to be good practice by facility design engineers. Increased ventilation to handle possible propane releases may also be included in the facility design. Often, the operation of such increased ventilation is tied to the gas detection system.

Source: Battelle

of alternative fuel. Necessary changes can include installing new refueling equipment or installing monitoring and ventilation equipment in maintenance and storage facilities.

Table 4 lists the typical modifications needed for transit bus maintenance and storage facilities for each type of alternative fuel. For alcohol fuels and propane, ventilation and electrical designs for gasoline facilities are often acceptable to the fire marshal or other local officials. However, both CNG and LNG require modifications to existing bus maintenance facilities and indoor storage areas. In all cases, check with local authorities for requirements in your area.

The costs of the maintenance and storage facility modifications and refueling facilities also depend on the size of the agency, as well as on state and local building codes. Table 5 lists the types of refueling facilities required for each alternative fuel. The table also shows estimates of the cost range for a refueling facility capable of refueling a 80 to 160 alternative fuel bus fleet.

For each alternative fuel, we also estimated the total costs of the necessary modifications to the fueling and maintenance facilities for a bus fleet of 160 alternative fuel buses. The cost of the changes to the building, mechanical systems, and electrical systems, as well as the cost of acquiring new equipment, was taken into consideration in the analysis. The estimates were done on the basis of square footage of fueling and maintenance facilities. Cost estimates include contractor overhead and profit (assumed to be 17%) and contingency (assumed to be 25%). We assumed that the facilities were converted in three phases to allow normal operations to continue and to serve a mix of diesel, gasoline, and alternative fuel vehicles. Table 6 shows the cost estimates for converting a 160-bus facility with 84,850 square feet of indoor storage, 19,250 square feet for the maintenance area, and a 9,120-square-foot fueling area.

At this time, CNG and LNG facilities have the highest capital costs.

Each alternative fuel facility must be custom designed to meet the specific needs of the transit agency. The cost of the facility can vary significantly. The cost estimates presented above should be viewed as representative figures for typical facilities. Consult Architect and Engineering firms experienced in alternative fuels for cost estimates for your particular site.

Emissions

With funding from DOE, West Virginia University's Department of Mechanical and Aerospace Engineering designed and constructed a transportable chassis dynamometer to test emissions levels from heavy-duty vehicles. The portability of this chassis dynamometer allows a large number of on-site emissions tests to be performed on buses and heavy-duty vehicles around the country. Before the unit was built, other options were considered, such as transporting vehicles to existing stationary dynamometers, or removing engines and transporting them to existing facilities. Both options were rejected because of expense and vehicle downtime.

The university has available a detailed description of the test procedures and the facility design.

Table 5. Refueling Facilities for a Fleet of 80 to 160 Alternative Fuel Buses

Alternative Fuel	Inventory Storage Options	Range of Incremental Capital Cost	Operating Cost	Comments
Diesel* (Baseline)	Underground Tank	Baseline	Low	Tank insurance would be needed.**
LNG	Above-ground Tank	$750,000 to $900,000	Low	
CNG (Fast-Fill)	Small High Pressure Accumulator Tank & Buffer	$750,000 to $1,500,000	Low to Medium	Compressors would require noise suppression.
CNG (Slow-Fill)	No Storage Needed	$600,000 to $900,000	Low	Noise suppression measures required for night operation.
Ethanol*	Underground Tank	$50,000 to $100,000	Low	Tank insurance would be needed.**
Methanol* (M100 or M95)	Underground Tank	$50,000 to $100,000	Low	Tank insurance would be needed.**
Biodiesel Blend*	Underground Tank	$0	Low	Tank insurance would be needed.**
Propane	Above-ground Tank	$100,000 to $150,000	Low	Fire suppression system required.

* Mobile fueling could be used, which eliminates capital costs, inventory costs, insurance costs, and is generally allowed by current codes/regulations.

** Tank insurance is insurance that covers fuel spills from the tank.

Table 6. Incremental Facility Costs for a Fleet of 160 Alternative Fuel Buses

(In millions of 1994 $)

	LNG	CNG	Alcohols*	Biodiesel	Propane
Fueling Facility	$0.90	$1.50	$0.10	N/C	$0.15
Maintenance Facility	$1.17	$1.08	N/C	N/C	N/C**
Bus Storage Facility	$1.44	$1.17	N/C	N/C	N/C**
Total	$3.51	$3.75	$0.10	N/C	$0.15

N/C = No change if facility is certified for gasoline

* Methanol and ethanol **See Note 1 of Table 4.

Source: Battelle